Renewable and Sustainable Energy Reviews 27 (2013) 225–233

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Selection of MCA methods to support decision making for renewable energy developments

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ARTICLE INFO

Article history:
Received 4 April 2013
Received in revised form
29 June 2013
Accepted 1 July 2013
Available online 23 July 2013

Keywords:
Multi criteria analysis
Sustainability
Decision making
Renewable energy

ABSTRACT

This paper presents a transferable and adaptable approach for selecting a suitable Multi-Criteria Analysis (MCA) method covering the stages of the 'MCA cycle' for decision making in the renewable energy sector. Selecting a suitable MCA method for an individual project or case study is a challenge due to the complexity of participatory sustainable decision making in this sector, as well as due to the complexity and large number of existing MCA methods. The methodology presented in this paper consists of both, generic and case-study specific parts.

The paper concludes that the methodology provides a transferable approach to systematically select a MCA method and to justify this selection. The methodology supports focusing on specific aspects, which are considered important and relevant for decision making processes. Furthermore, the case study's generic decision making situation allows the methodology to be applied broadly within the renewable energy sector. Moreover, the MCA methods and selection criteria identified and reviewed provide a broad application potential to assist MCA method selection in the energy and renewable energy sectors.

Contents

1. Introduction

Multi-criteria analysis (MCA) can be defined as formal or structured approaches for individuals or groups to determine overall preferences among alternative options by taking account of multiple criteria and indicators (C&I) [1–3]. MCA approaches show explicitly how the alternative options contribute to the various C&I and contain a judgment process, which usually comprises a relative weighting process. MCA approaches can be exercised for identifying a single most preferred option or for a ranking of alternative options, a short list with a limited number of options for further assessment, as well as for determining acceptable and unacceptable options [2]. They have become increasingly popular in decision making on sustainable developments and on energy systems due to their ability to consider

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http://dx.doi.org/10.1016/j.rser.2013.07.001

and simultaneously evaluate a number of economic, environmental, social and technological aspects, which complex systems require [4]. For that purpose MCA approaches offer algorithms to systematically aggregate multi-dimensional information to reduce complexities in a transparent way (e.g. [5]). They proved to be of assistance in comprehensive decision processes and in overcoming implementation barriers by structuring the problem, identifying less robust and uncertain components of energy systems and involving different stakeholders in challenging and difficult decision making situations [6].

In literature, there are several approaches to classify MCA approaches. A popular form of MCA is Multi-Criteria Decision Analysis (MCDA), which is also known as multi attribute decision analysis (MADA) [2]. Further notable is that the terms 'MCDA', as well as 'MCDM' (Multi-Criteria Decision Making) are often synonymously used for MCA.

Moreover, Buchholz et al. [6] and others [7–9] are describing two main categories: Multi Objective Decision Making (MODM) and Multi Attribute Decision Making (MADM) approaches. The main difference between the two groups of approaches is the number of possible alternatives, which are evaluated. For MODM an indefinite number of alternatives are defined by a set of constraints on a vector of decision variables resulting in an optimized alternative. On the other hand, for MADM approaches, which are usually employed for environmental decision making problems [10], a certain finite number of alternatives, which are given explicitly, are developed and assessed against a set of principles or C&I. These are often expressed as qualitative and/or quantitative attributes [1,7,10,11].

According to Belton and Stewart [1] (adopted by others, e.g. [6,7]) MADM approaches can generally be differentiated into three broad categories to illustrate their application ranges more directly. These three categories are: (i) value measurement models, (ii) goal, aspiration and reference-level models and (iii) outranking models. The approaches in the first category follow the Multi Attribute Value Theory (MAVT) and its extension the Multi Attribute Utility Theory (MAUT), which works with utility functions for additional inclusion of risks and uncertainties. Belton and Stewart [1] describe goal, aspiration and reference-level models as goal programming methods, which employ algorithms based on mathematical programming to meet the goals, aspirations or reference levels as much as possible. Outranking models compare scenarios and alternatives against each criterion and its indicator on a pairwise basis [12]. In this process incomparabilities are identified, as well as preferences and indifferences are assessed. The aggregation of preferences in respect to each criterion and its indicator results in a scenario or alternative, which outranks others. However, in contrast to MAUT the aim is usually not to identify a single highest scoring alternative, but rather to involve multiple stakeholders in a process to advise each other [13].

MCA methods can be considered for different stages of multi-criteria decision making. Wang et al. [14] reviewed MCDA methods for C&I selection, C&I weighting, evaluation, and final aggregation. However, with respect to the latter stage Guitouni and Martel [15] believe that aggregation procedures and MCA methods are confusing concepts and have been used in the same way. This is not surprising since some methods, such as Analytic Hierarchy Process (AHP) can contribute to more than one decision making stage. Moreover, Buchholz et al. [6] illustrate the stages of a 'MCA cycle', which is a separate cycle within an 'adaptive multi-stakeholder management cycle'. These stages commonly, but not exclusively comprise: (i) C&I weighting or ranking, (ii) assessment and ranking of alternatives and (iii) sensitivity analysis.

Against this background, this paper presents a methodology to select suitable MCA methods covering the stages of the 'MCA cycle' for decision making in the renewable energy sector, which is challenging due to the mentioned complexity of participatory sustainable decision making in the energy sector, as well as due to the large number and complexity of MCA methods.

2. Methodology for MCA method selection

The methodology presented in this paper builds on literature (e.g. [7,16]). For instance, Guitouni and Martel [15] provide a framework to develop a selection methodology and tentative guidelines to support selecting an appropriate MCDA method. Furthermore, Buchholz et al. [6] analyzed the applicability of four MCA tools for bioenergy systems assessments by scrutinizing their structural approach using a set of nine criteria to evaluate methodological implications, technical aspects and the application value of MCA methods.

Following the methodology recommendations from the reviewed literature, the methodology presented in this paper consists of both, generic and case-study specific parts. First, MCA methods and criteria to select MCA methods from literature were identified and reviewed. Then, the methodology was applied in a case study involving the main steps: development of a generic decision making situation, development of a set of appropriate criteria for MCA method selection, pre-selection of MCA methods and scoring of the pre-selected MCA methods against the developed selection criteria. In the subsequent sections these processes are described and discussed in detail.

2.1. Identification of weighting and MCA methods applied in the energy and renewable energy sectors

MCA methods have been extensively addressed in academic articles covering the energy sector in general, as well as the renewable energy sector. Table 1 summarizes reviewed literature on weighting and MCA approaches applied in these sectors. The table illustrates only a certain fraction of studies in these sectors. However, in contrast to similar summaries (e.g. [4]) it focuses on more recently applied methods, as well as stakeholder involvement. For a detailed review of methods in the different stages of multi-criteria decision making for sustainable energy we recommend Wang et al. [14]. Further rather theoretical studies in this field include for instance Chatzimouratidis and Pilavachi [17], Pilavachi et al. [18], Chatzimouratidis and Pilavachi [19].

It can be concluded that the vast number of applied MCA methods to support sustainable decision making in the energy sector in general, as well as the renewable energy sector makes it imperative to take a systematic approach to select MCA methods for individual projects or case studies. Further notable is that frequently several different suitable weighting and/or MCA methods are applied to a decision making problem to look at problems from various angles. This can help cross-checking and verifying the validity of MCA method results before arriving at the final ranking of alternatives.

2.2. Criteria for selecting MCA methods

Criteria for selecting MCA methods from literature against which MCA methods can be scored are described and summarized (Table 2) in this section.

Guitouni and Martel [15] provide general tentative guidelines to help choosing an appropriate MCA (specifically MCDA) method. Their first guideline is to determine, whether a decision is made by one or many decision makers. Second, the preference elucidation and modeling has to be considered. This guideline is divided into: (a) the preference elucidation mode (e.g. pairwise comparison), (b) the timing of preference elucidation, (c) the global decision

Table 1
Summary of weighting and MCA methods applied in the energy and renewable sectors.

Scope	Weighting and/or MCA method	Special features	Stakeholder involvement	Source
Sustainability framework to assess bioenergy systems	Not specified MCDA method	Least cost optimization models for scenarios. Life cycle impact assessment (LCIA) for C&I performance assessments. Numeral Unit Spread Assessment Pedigree (NUSAP) approach to classify qualitative and quantitative uncertainties.	Decision conferencing for C&I selection (different stakeholders). Experts for C&I performance assessments	[20]
Sustainability assessment to select a country's energy system	MCA based on Analysis and Synthesis of Index at Information Deficiency (ASPID) methodology and a General Sustainability Index	Comparison of MCA to single criterion analysis. Stochastic modeling of uncertainty, as well as normalization of indexes by using Non-numeric (ordinal), Non-exact (interval) and Non-complete information (NNN-information) with respective reliability and probability	No	[8]
Renewable energy scenarios and participatory multi-criteria analysis (PMCA)	SIMOS and Preference ranking organization method for enrichment evaluation (PROMETHEE) II	Resource-intensive combination of scenarios and PMCA. Narrative storylines for scenarios. C&I performance assessments based on own modeling, existing databases and expert assessments. 'Silent negotiation' technique for C&I ranking	Scenario development and improvement of developed C&I (energy stakeholders and experts). Experts and stakeholders for C&I performance assessments and weighting.	[4]
MCA for bioenergy systems	Analytic Hierarchy Process (AHP), DELTA , PROMETHEE II, Novel Approach to imprecise Assessment and Decision Environments (NAIADE)	Criteria for MCA method selection. Sensitivity analyses on C&I weighting and performance assessment results	Stakeholders and experts involved in C&I weighting and performance assessments	[6]
Appraisal of national energy scenarios – renewable energy use	SIMOS and PROMETHEE (Decision Lab)		Stakeholder involvement in scenario and C&I development, individual C&I weighting and discussion of MCA results. Experts involved in C&I performance assessments	[21]
Sustainable development of a city's energy system	MCA based on fuzzy sets synthesis technique		No	[22]
Alternative power generation scenarios	PROMETHEE	Comparison of MCDA and Cost-Benefit-Analysis (CBA)	Official authorities involved in scenario development	[23]
Small-scale energy technology applications in local governments	MACBETH (Measuring Attractiveness by a Categorical Based Evaluation TecHnique)	Performance assessments involving LCA and CBA (including calculation of Net Present Values)	Households, energy professionals and local council members involved in C&I performance assessments and weighting	[9]
Optimization of decentralized energy systems	Elimination et choice translating reality (ELECTRE) III	Sensitivity analysis in relation to the preference, indifference, veto thresholds and importance coefficients	Local authorities and private actors involved in C&I weighting and sensitivity analysis	[24]
Formulation of sustainable technological energy priorities	MCDA with linguistic variables use (fuzzy set theory)	Linguistic decision support system (L-DSS) incorporating linguistic ordered weighted averaging (LOWA), the 2-tuple LOWA and the OWMAX (ordered weighted minimum operators) to deal with imprecision	Working groups with national energy actors involved in C&I and alternatives selection, C&I weighting and performance assessments	[25]
Public and stakeholder perceptions of bioenergy scenarios	Simple additive approach		Policy stakeholders and informed local members of the public involved in scenario development, C&I weighting and performance assessments, as well as appraisal of final weighted scores	[26]
Energy policy and production site planning for a city	Integrated fuzzy VIKOR (VIšekriterijumsko KOmpromisno Rangiranje) and AHP methodolgy	Integrated methodology to select energy alternatives and sites	Experts involved in C&I weighting	[27]
Land suitability assessment for spatially distributed anaerobic digester	AHP	Geographic Information System (GIS) modeling to locate optimal sites. Performance assessments for distance-related C&I combined with weights obtained from AHP application	No	[28]
Evaluation of alternative fuels for electricity generation	Analytic Network Process (ANP) (Super Decisions)	LCA use	Experts involved in C&I weighting	[29]

making preference structure obtained using the aggregation procedure and resulting from that (d) the specific alternative order type. Thirdly, the decision makers' desired outcomes have to be taken into account. An example for such an outcome can be a ranking of alternatives. The fourth guideline is about a MCA method's ability to process available input data properly. Required data should easily be provided by stakeholders. Where qualitative data is used, it can make a significant difference to the quality of decision making, if a MCA method is capable to incorporate that data. Another guideline is about dealing with the compensation degree of a MCA method. However, Guitouni and Martel [15] admit that this aspect is difficult to evaluate. They also advise to

Table 2
Criteria for MCA method selection from literature.

Selection criteria	Source
Multi-stakeholder inclusion	[6,7,15]
Determining of C&I weights	[7,15,16]
Handling of qualitative and quantitative data	[6,7,15,16]
Shape and form of final results	[15,16]
Compensation degree	[15]
Meeting the method's fundamental hypothesis	[15]
Support by a software package	[15]
Measures to deal with uncertainty	[6,7]
Country of application	[7]
Type of data used	[7]
Nature and context of the problem	[7]
Spatial scale	[7]
Type and selection of stakeholders	[7,13]
Inclusion of C&I hierarchies	[6]
Use of thresholds	[6]
Ease of computation	[6,13]
Dynamic re-evaluation	[6]
Transparency and likely user acceptance of results	[6,13]
Communication of decision process and results	[6,13]
Core process	[16]
Necessity to quantify the relative importance of C&I	[16]
Number and type of outranking relations	[16]
Control of consistency	[16]

bear in mind how MCA methods meet their fundamental hypotheses. However, the information this criterion provides can be regarded as being more descriptive and less suitable for MCA method comparison and selection. The final guideline they mention is about the availability of software packages to apply a MCA method. The authors raise concerns that in many cases decision aid package software is applied without deeper knowledge of the procedure. On the other hand, they argue that it can occur that a MCA method, which would be suitable for a decision making situation is not employed simply because a software package is not user-friendly and/or does not allow integration of a variety of MCA methods.

Mendoza and Martins [7] critically reviewed and systematized applied MCA (specifically MCDM) methods in natural resource management using a number of criteria and characteristics. The most relevant of those indicate, (a) if a MCA method deals explicitly with uncertainty, (b) if more than one decision-maker is involved and (c) the moment when modeling of C&I preferences through stakeholder's involvement takes place. In regard to the last aspect, Mendoza and Martins [7] reviewed academic papers using three different categories: (a) ‘a priori’, (b) interactive and (c) posterior articulations. ‘A priori’ means that the stakeholder involvement starts with the modeling of preferences. On the other hand, ‘interactive articulation’ of preferences results in the most preferred solution or alternative through stakeholders answering specific questions. For ‘posterior articulation’ of preferences ‘non-dominated’ solutions are generated prior to the evaluations made by the stakeholders. When elucidation methods are carried out in group decision making situations the individual stakeholder preferences can be synthesized in various ways, whereas Mendoza and Martins [7] mention that aggregating has been established as a main aspect in methodological adaptations of MCA to group decision making. Furthermore, they point out that many aspects in the field of natural resources management cannot be estimated or predicted sufficiently, which contributes to uncertainty in decision making. However, if uncertainty is not addressed sufficiently, suboptimal or even inappropriate alternatives are potentially selected and implemented ultimately resulting in unsustainable outcomes. Other selection criteria mentioned [7] (e.g. ‘country of application’, ‘spatial scale’, ‘nature and context of problems’ or ‘type of data used’) provide more descriptive information and, therefore, are less relevant for the selection of MCA methods. The mentioned criterion ‘type and selection of stakeholders’ can also be regarded as being irrelevant for MCA method selection, this process usually takes place as a separate step earlier in a decision making process (e.g. [2,30,31]).

Buchholz et al. [6] analyzed how applicable MCA methods for bioenergy systems assessments are by scrutinizing their structural approach using nine selection criteria. The first selection criterion covers ‘stakeholder inclusion in decision making’ and takes account of the fact that renewable energy developments, such as bioenergy developments, typically involve a relatively high number of stakeholders. In this connection, it is pointed out that many of past projects were unsuccessful when stakeholders were not engaged appropriately. The second selection criterion covers the ‘application of qualitative data’. Technical aspects are taken into account by three criteria. ‘Measures to deal with uncertainty’ is the first among those and is justified by the significance and varied forms of uncertainty, which can be dealt with by MCA methods at the different stages of a decision making process. Another technical aspect is the ‘inclusion of criteria hierarchies’. Hierarchies assist in reducing complexities and allow facilitated communication of decision making results and strategies to stakeholders without technical knowledge. The third technical criterion ‘use of thresholds’ is about implications of applied numerically precise thresholds, which are helpful in dealing with data uncertainty. Four criteria cover the applicability of MCA methods. ‘Ease of computation’ addresses the technical user-friendliness and flexibility of MCA methods. In this respect, the criterion also takes into account the differences among MCA methods regarding problem structuring, parameter setting and sensitivity analysis. Related to this criterion is ‘dynamic re-evaluation’, which is about a MCA method's ability to allow re-evaluating decisions based on new structures, insights or data. This ability supports flexible and adaptive learning cycles as proposed by Gamboa and Munda [32]. An important aspect when involving numerous stakeholders is the application of simple math and intuitive methods to improve the acceptance of MCA methods results. The criterion ‘transparency’ covers this aspect. Related to this criterion is the last criterion ‘communication of decision process and results’. Decent abilities of MCA methods in respect to this aspect can be critical when numerous stakeholders are involved. Apart from aspects related to stakeholder involvement and easy handling, considering these aspects covering acceptance and understanding are also recommended by Huang et al. [13] under certain circumstances.

Özcan et al. [16] describe a comparative analysis of MCA (specifically MCDM) methodologies and implement a warehouse location selection problem. Although, not specifically focused on sustainability or energy decision making, their analysis and comparison of MCA methods including AHP, TOPSIS, ELECTRE I–III provide useful inputs for the process of selecting an appropriate MCA method. The several methods reviewed in the paper are differentiated by seven characteristics or criteria: (a) core process, (b) necessity to quantify the relative importance of C&I, (c) determining of C&I weights, (d) number and type of outranking relations, (e) consistency check, (f) problem structure and (g) final results. The first characteristic provides rather descriptive information and can be regarded as being less suitable for MCA method selection. The criteria about quantifying the relative importance of C&I and determining C&I weights are both focusing on the ‘MCA cycle’ step ‘C&I weighting or ranking’. The first criterion does not serve to discriminate sufficiently between methods to support the selection process, because almost all MCA methods require the relative importance of C&I to be quantified. On the other hand, the second criterion can be considered as being important, because C&I weighting is an essential part of MCA methods and differences between methods in this regard are significant. Not every MCA method has a specific weighting method incorporated

and for some C&I weights are provided without any calculations. However, for the latter methods commonly linear and vector normalizations are used [33]. The described criterion 'number and type of outranking relations' can be regarded as being too specific and focused on outranking methods for selecting MCA methods. On the other hand, it can be regarded as being important to measure and control the consistency of stakeholders' preferences. The criterion 'consistency check' shows, if MCA methods allow controlling consistency. The criterion 'problem structure' covers numbers of C&I and alternatives, which have to be compared, as well as a method's ability to handle quantitative and/or qualitative data. This aspect is only relevant for decision making problems with large numbers of C&I and alternatives, and as mentioned previously, only if qualitative data is used. The criterion 'final results' covers the shape in which acquired MCA results are available. This criterion can be regarded as a non-essential feature for selecting suitable MCA methods.

3. Application of the methodology for MCA method selection

This section illustrates how the methodology for MCA method selection was applied. First, the case study is described. Second, the most appropriate set of MCA method selection criteria was developed based on the reviewed literature (Section 2.2). Then, some MCA methods were pre-selected and compared against these criteria to choose the most appropriate MCA method for the case study.

3.1. Case study description

For the application of the methodology to select a MCA method, basically a generic decision making situation was assumed, in which renewable energy developments are planned. In terms of the MCA method selection itself, it was further assumed that MCA methods cover the following steps of the MCA cycle: (i) C&I weighting or ranking, (ii) assessment and ranking of alternatives and (iii) sensitivity analysis. Also, it was assumed that stakeholders are involved in a single event for C&I weights determination. In terms of C&I performance assessments, it was assumed that the performances are assessed objectively and that stakeholders agree exclusively on employing quantitative C&I. Choosing this generic decision making situation was intended to demonstrate the broad application potential of the presented approach to select MCA methods in the renewable energy sector.

3.2. Choice of criteria for MCA method selection

Based on the literature review (Section 2.2), a set of most appropriate MCA selection criteria for the case study was developed. Table 3 illustrates these criteria, which are also briefly described for clarification.

The illustrated selection criteria were chosen by considering their relevance for the case study, but also by bearing in mind how independent they are from each other. For instance, criteria related to 'transparency', 'inclusion of C&I hierarchies' and 'communication of decision process and results' can be employed as separate criteria. However, when looking at the descriptions of criteria [6], relatively strong interrelationships can be identified. Good communication leading to easy comprehension is supported by transparency, but on the other hand good communication assists in increasing acceptance and transparency. C&I hierarchies help to reduce complexity and as a consequence facilitate communication or processes and results. This again improves stakeholder comprehension. Therefore, for the case study these three criteria were merged into a single criterion called 'transparency and communication'. In general, the selection criteria were kept as independent as possible for the case study. However, some interrelationships exist. For instance the criterion 'multi-stakeholder inclusion' is related to the criteria 'user friendliness and flexibility', as well as 'transparency and communication' to a certain extent. Also, it has to be highlighted that a selection criterion comparing, whether MCA methods are able to process qualitative C&I data was not required, because as mentioned (Section 3.1) only quantitative C&I were considered. Also, employing exclusively quantitative C&I, which can be assessed objectively, affected the scoring of the MCA methods against the selection criterion 'measures to deal with uncertainty', as uncertainty related to determining C&I weights could be focused on. This demonstrates that the processes of choosing appropriate selection criteria and the selection of MCA methods itself depend heavily on a project's or case study's specific circumstances. In this connection, particularly, the way multiple stakeholders were involved plays a major role. For instance, if stakeholders want to be involved in a single event for C&I weights determination – as it was assumed in case study's decision making situation (Section 3.1) – C&I weighting has to be undertaken 'a priori'. Therefore, 'a priori' C&I weighting had to be considered as a prerequisite in selecting MCA methods in the case study. Similarly, in such a decision making situation in which stakeholders agree exclusively on quantitative C&I with relatively certain performance values, capabilities of MCA methods to deal with qualitative C&I and uncertainty are not required or only relevant to a certain degree, respectively.

3.3. Pre-selection of MCA methods

In this section it is described how three MCA methods were pre-selected in order to test the methodology in the case study. This pre-selection was mainly based on the popularity of MCA methods.

Huang et al. [13] identified and classified over 300 papers on environmental applications of MCA (specifically MCDA), which were published between 2000 and 2009. The papers were classified by their environmental application area, decision or intervention type and three main MCA approaches were identified and employed for their analysis: 'Outranking', 'AHP/ANP (Analytic Network Process)' and 'MAUT/MAVT'. When looking at papers about MCA methods in the application area 'Energy' published between 2000 and 2009, AHP/ANP

Table 3
Criteria for MCA method selection for the case study.

Selection criteria	Description:
Measures to deal with uncertainty	To what degree does a MCA method address uncertainty in its different stages?
User-friendliness and flexibility	How easy is the computation of MCA processes? Is the MCA method user friendly, flexible and adaptive and does it allow re-evaluations?
Transparency and communication	How simple and intuitive is a MCA method to increase transparency and stakeholder acceptance? Are hierarchies incorporated to help reducing complexity and to support communication of processes and results in order to improve stakeholder comprehension?
Multi-stakeholder inclusion	How easy is it to involve multiple stakeholders in the MCA process?

approaches were predominantly employed, followed by PROMETHEE, ELECTRE and MAUT/MAVT methods accounting for 42, 12, 9 and 9% respectively. Moreover, a trend towards AHP/ANP methods, indicated by the growing number of their applications over that decade, was identified. AHP/ANP methods were also identified as the most popular approaches (48%) when looking at published papers about applications of MCA methods with stakeholder participation.

For the case study, most popular MCA methods according to Huang et al. [13] were compared against the selection criteria (Table 3). These pre-selected MCA methods were: AHP [34], DELTA [35] and PROMETHEE [36] representing MAVT, MAUT and outranking methods, respectively [37]. In order to compare only one method representing a main MCA approach, the popular ELECTRE method was excluded from the comparison due to its lower popularity compared to PROMETHEE, which is also an outranking method. Also, AHP was focused on in this comparison rather than ANP, because AHP is significantly more applied in the environmental management and agriculture application area [38].

Notable is that MCA combined fuzzy methodologies, which involve a series of mathematical steps and are basically fuzzy extensions to conventional MCA methods (e.g. fuzzy outranking methods and fuzzy utility theory), have also been applied in energy decision making situations various times (e.g. [25,39,40]). However, due to several reasons they are unpopular within the MCA community and have predominately been discussed in academic literature and conducted experimentally [2]. For instance, particularly for AHP and ANP the accuracy of the fuzzy approach is criticized [41]. Therefore, the practical value of MCA combined fuzzy methodologies can be substantially questioned and it is even assumed that their future application will be flawed in regard to better decision making [38]. Consequently, these approaches were excluded from the process of selecting MCA methods in the case study.

3.4. Scoring of pre-selected MCA methods

Each of the three pre-selected MCA methods ‘AHP’, ‘DELTA’ and ‘PROMETHEE’ was compared against the four selection criteria described previously (Table 3). In this process, the MCA methods were assessed using a three-point scale with ‘low’, ‘medium’ and ‘high’ scores. Additionally, specific freely downloadable or commercially available software packages were considered to compare them against some of the selection criteria:

- ‘Super Decisions’ (AHP)
- ‘DecideIT’ (DELTA method)
- ‘Decision Lab’ (PROMETHEE II)

The software packages were selected due to their common applications in related fields such as renewable energy, natural resource management or participatory assessments. Based on a literature review and by considering the case study’s circumstances (Section 3.1), the software packages' scoring against some of the selection criteria contributed to identifying the most suitable MCA method and its software package for the case study. The following two examples illustrate how the scoring against two selection criteria was undertaken.

3.4.1. User friendliness and flexibility

‘User-friendliness and flexibility’ was one of the four criteria against which the AHP, DELTA and the PROMETHEE II methods were compared. The scores for this criterion reflect several aspects including ease of computation and technical user-friendliness of the reviewed methods and their software packages, as well as their flexibility and adaptability in terms of allowing re-evaluation of decisions with new data inputs or structures.

‘Super Decisions’ scored ‘medium’ against this criterion. It allows easy computation with its straightforward structure and its simple framework to build and assess scenarios and alternatives. Particularly, data input of the pairwise comparison data is perceived as simple and convenient by users [2]. Furthermore, data input requirements are minimal and free downloadable software package versions of ‘Super Decisions’ are available. Looking at these aspects in isolation the user friendliness of ‘Super Decisions’ is high. However, it is relatively difficult to apply sensitivity analyses and dynamic re-evaluations. Performing sensitivity analyses is difficult, because the software package's capability for analysis is restricted to one criterion at a time. In terms of dynamic re-evaluations, direct comparisons between existing assessments and assessments with new data input are not possible. Comparing those assessments is only feasible indirectly through re-structuring data and running separate assessments [6,15]. Also, the ‘rank reversal’ phenomenon [42] has to be considered when decisions want to be re-evaluated. However, this phenomenon has only to be taken account of, in cases where C&I performance values are included in the assessments.

In terms of ease of computation and technical user-friendliness, the capabilities of the commercially available DecideIT software package can be considered as decent with its advanced user interface and intuitive logic to structure and define C&I, as well as conducting sensitivity analysis. Furthermore, it requires low minimum data input. However, if minimization is the goal of the decision making situation, this software package of the DELTA method requires manual inversion of data. For example, the goal air pollution reduction has to be converted to air quality improvement. This means an additional step, which reduces DecideIT's user friendliness. As for ‘Super Decisions’, re-evaluating decisions is difficult as new data input cannot be integrated, which disallows direct comparisons between old and new assessments [6]. Therefore, the case study's score for ‘user friendliness and flexibility’ was considered to be ‘medium’.

The available software package ‘Decision Lab’ scored ‘high’ against ‘user friendliness and flexibility’. It allows relatively easy computation in all its application stages. Technical user friendliness is supported by an easy-to-use interface to structure the decision making problem and to input data. This software package of PROMETHEE II also offers a user-friendly sensitivity analysis with the possibility to have numerous perspectives on the problem. This includes the use of ‘walking weights’ and side-to-side assessments of scenarios and alternatives [6,15]. In terms of dynamic re-evaluation, ‘Decision Lab’ is equally well capable, which allows engaging in flexible and adaptive learning cycles. It is the only reviewed software package, which offers direct comparisons between existing and new assessments of scenarios and alternatives through its scenarios and alternatives analysis, which also allows structures to be changed for these comparisons [6].

3.4.2. Multi-stakeholder inclusion

Another criterion against which the three MCA methods AHP, DELTA and PROMETHEE II were compared against was ‘multi-stakeholder inclusion’. This criterion is about an approach's capability to involve multiple stakeholders in the MCA process easily. Naturally, the two criteria ‘user friendliness and flexibility’, as well as ‘transparency and communication’ are connected to this criterion to a certain extent. Thus, the scores of the methods against those criteria also contain and cover elements of the approaches' abilities to include multiple stakeholders. In line with the scenario description (Section 3.1), the three MCA methods AHP, DELTA and PROMETHEE II and their software packages were evaluated

regarding their coverage of some or all of the mentioned steps of the MCA cycle. In other words a holistic perspective looking at all those stages was necessary to determine an approach's capability for multi-stakeholder involvement. Also in line with the scenario description (Section 3.1), it has to be taken into account that it was assumed that stakeholders express their opinions towards C&I priorities 'a priori'. All three reviewed MCA methods allow the incorporation of C&I weighting during that stage of the decision making process.

The AHP method scored 'high' against the selection criterion when keeping the case study in mind. One of the core elements of AHP is the conversion of subjective assessments of relative importance to overall weights [2,6]. The method is the only of the three reviewed MCA methods, which works with a specific procedure to determine C&I weights – pairwise comparisons between C&I – and through that provides ready-to-use C&I weights or rankings. Pairwise comparisons significantly reduce the likelihood of stakeholders making mistakes and rough estimations by deriving ratio scale priorities, while eliciting utility functions is not required [17]. This allows stakeholders to be easily involved. The method also allows group decision making procedures in assessing and ranking alternatives, as well as in the sensitivity analysis stage [6,7].

The DELTA method scored 'medium' against the criterion 'multi-stakeholder inclusion'. This score is justified, because the method requires external aggregation of C&I weights through pairwise comparison. This makes stakeholder involvement more difficult. However, the method allows stakeholder involvement in scenarios and alternatives assessment and sensitivity analysis, when uncertainty of C&I weights is taken account of [6].

The PROMOTHEE II approach also scored 'medium' against the criterion 'multi-stakeholder inclusion'. Like the DELTA method it relies on externally derived C&I weights or rankings. However, stakeholders can be involved in the assessment of scenarios and alternatives, as well as in the sensitivity analysis. Furthermore, it allows analyzing group decisions and comparing individual opinions with each other by assigning scenarios to each individual stakeholder's opinion [6].

4. Results and discussion

The scores of the three different MCA methods compared against the selection criteria are summarized below (Table 4):

In the case study, the AHP method scored best with three 'high' scores and one 'medium' score, followed by the DELTA method with two 'high' and two 'medium' scores. PROMETHEE II only scored 'high' once, 'medium' twice and 'low' against one criterion. Interestingly, this MCA method scored best against the criterion 'user friendliness and flexibility', against which the other methods only achieved a 'medium' score. Conversely, PROMETHEE II scored worst against 'measures to deal with uncertainty', whereby the results of the other two methods are particularly well against this criterion. Further, it can be observed that the scores for the AHP and Delta methods against the selection criteria only differ in regard to 'multi-stakeholder inclusion', which is not surprising when bearing in mind how closely MAVT and MAUT are related [1]. The difference in scores is mainly due to the fact that AHP is the only of the three methods, which works with a specific participatory procedure to determine C&I weights — pairwise comparisons — instead of relying on external aggregation of C&I weights.

Table 4
Scoring results of reviewed MCA methods for the case study.

Selection criterion	MCA method		
	AHP	DELTA	PROMETHEE II
Measures to deal with uncertainty	*High*	*High*	*Low*
User friendliness and flexibility	*Medium*	*Medium*	*High*
Transparency and communication	*High*	*High*	*Medium*
Multi-stakeholder inclusion	*High*	*Medium*	*Medium*

When reflecting and concluding on the scoring process, it has to be addressed that several factors and assumptions influenced the results significantly. First, it has to be considered against what the MCA methods were compared, i.e. the selection criteria. Choosing them was to a certain extent subjective and their choice influenced the results of the MCA method selection substantially. In other words, using different criteria against which the methods were compared, could have led to diverging results. The same applies to what was scrutinized against the criteria, i.e. the three MCA methods. Although, their pre-selection was justified by their popularity and common use in the energy sector, the focus on specific software packages representing those methods when compared against some of the selection criteria, was rather subjective. However, in either instance the subjectivity stemmed from the case study's decision making situation, which had to be considered (Section 3.1). Huang et al. [13] confirm this by highlighting the importance of considering the complexity of the MCA method selection in respect to influencing scientific, social and technical factors, but also in regard to an understanding of the process requirements, as well as the degree of available knowledge about the specific decision making problem. For the case study the most influencing factors in this respect were the fact that the focus was on C&I weights excluding C&I performance values, as well as quantifiable C&I. In case the stakeholders would have chosen predominantly qualitative C&I, another MCA method selection process resulting in different outcomes would have been required. Features of MCA methods in regard to qualitative C&I, as well as the incorporation of C&I performance values in the decision making process was therefore not important to the different stages of the MCA method selection process in the case study. This again demonstrates that the process of choosing appropriate MCA methods heavily depends on a project's or case study's specific circumstances, which is also confirmed by Guitouni and Martel [15] who state a lack of a single ideal and appropriate MCA method for all decision making situations. Consequently, it could be argued that the complex process of selecting the most suitable MCA method could paradoxically call for applying a MCA method to help choosing. This however would result in a 'chicken-or-egg situation', because to employ a MCA method to help choosing a MCA method would imply selecting a MCA method in the first place, which would still leave one wondering how to select that method. Further, it can be observed that the selection criteria deemed to be relevant (Section 2.2) were predominantly criteria with emphasis on acceptance, understanding and interaction with the MCA method. Compared against them AHP is a strong MCA method. Buchholz et al. [6] and Chatzimouratidis and Pilavachi [17] explain that the method's general popularity and wide use is mainly due to its logical approach and simplicity facilitating these aspects, whereas Huang et al. [13] regard available software packages, expertise and particularly active user groups as possible reasons for this popularity. In this connection it is notable that AHP lacks qualities in regard to addressing dependencies and interrelations between C&I. Conversely, its extension ANP has distinctive qualities in this regard, which can lead to substantial improvements in decision making. Due to this reason it is expected that ANP will gain more popularity compared to AHP in the future [38]. However, due to ANP's higher complexity, 'user friendliness and flexibility', 'transparency and communication' as well as 'multi-stakeholder inclusion' can be regarded as being

reduced compared to AHP. As mentioned (Section 2.2), Huang et al. [13] advise MCA users to select methods based on aspects related to stakeholder involvement, acceptance, easy handling and understanding when MCA methods results can be expected to be robust. Such a robustness of MCA methods is generally the case. When applying different MCA methods to the same decision making problem, it was observed that although the ranking of alternatives may change, generally the same alternatives come out at the top regardless of the MCA method employed [13]. This is due to the mathematical phenomenon that the best ranking alternative(s) is/are often so much better than the remaining alternatives so that the differences between MCA methods are too minor to significantly change the outcome. The reason for this is that those differences are most probably affecting all alternatives equally within C&I assessment levels unless all MCA methods would be biased towards a single alternative, which is highly unlikely [43,44]. The phenomenon was particularly observed for decision making situations with a small number of alternatives [13]. Therefore, for these cases distinctive qualities of MCA methods would be less significant than for instance selecting most appropriate C&I or involving appropriate stakeholders. Nevertheless, regardless the number of alternatives, selecting a suitable MCA method in the described systematic manner is an effective and valid approach for decision making situations, because it illustrates and justifies why a particular MCA method makes more sense than other compared methods when specific aspects are relevant and focused on. Furthermore, when applying a MCA method, which was selected by employing the presented methodology, the identified limitations and disadvantages of the method with respect to the selection criteria can be considered more easily. This can facilitate processes in similar decision making situations, particularly in the renewable energy sector. In this regard, the presented methodology is advantageous compared to other approaches to select MCA methods (e.g. [6]), due to its generic nature. Although, similar MCA selection criteria are presented in related works [6,7,15,16], a methodology to systematically select MCA methods by developing an appropriate set of selection criteria, pre-selecting MCA methods and scoring the pre-selected methods against the developed set of selection criteria has, to our knowledge, not been published yet.

5. Conclusions

This paper provides a generic approach to select a suitable MCA method covering the stages of the 'MCA cycle' for decision making in the renewable energy sector. Selecting a suitable MCA method for an individual project or case study is challenging due to the complexity of participatory sustainable decision making in this sector, as well as due to the complexity and large quantity of existing MCA methods.

The provided methodology for selecting MCA methods consists of both, generic and case-study specific parts. First, it is proposed to identify and review MCA methods and criteria to select MCA methods from literature. Second, case study specific steps are proposed to be applied including: development of a set of appropriate criteria for MCA method selection, pre-selection of MCA methods and scoring of the pre-selected MCA methods against the developed selection criteria.

In general, the process of selecting appropriate MCA methods depends heavily on a project's or case study's specific circumstances. However, the case study's decision making situation presented in this paper was deliberately developed in a rather generic way allowing a wide range of application potential for decision making situations within the renewable energy sector. The criteria for MCA method selection deemed to be relevant were predominantly criteria focusing on acceptance, understanding and interaction with the MCA method. AHP scored best when pre-selected MCA methods were compared against the selection criteria.

Although, in certain circumstances the results of MCA methods do not differ significantly, selecting suitable MCA methods in the proposed systematic manner is an effective and valid approach, because it helps focusing on specific aspects, which are considered important and relevant for decision making processes. Therefore, for similar research or decision making situations the proposed methodology for MCA selection can be employed, although different criteria and/or MCA methods may be chosen for the selection process. Furthermore, the identified and reviewed MCA methods and selection criteria provide a broad application potential for MCA method selection in the energy and renewable energy sectors.

Reference

[1] Belton V, Stewart TJ. Multiple criteria decision analysis: an integrated approach. 1st ed.. Norwell, Massachusetts: Kluwer Academic Publishers; 2002.

[2] Department for Communities and Local Government. Multi-criteria analysis: a manual. Wetherby: Communities and Local Government Publications; 2009.

[3] Hung M, Ma H, Yang W. A novel sustainable decision making model for municipal solid waste management. Waste Management 2007;27:209–19.

[4] Kowalski K, Stagl S, Madlener R, Omann I. Sustainable energy futures: methodological challenges in combining scenarios and participatory multi-criteria analysis. European Journal of Operational Research 2009;197:1063–74.

[5] Stirling A. Analysis, participation and power: justification and closure in participatory multi-criteria analysis. Land Use Policy 2006;23:95–107.

[6] Buchholz T, Rametsteiner E, Volk TA, Luzadis VA. Multi criteria analysis for bioenergy systems assessments. Energy Policy 2009;37:484–95.

[7] Mendoza GA, Martins H. Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. Forest Ecology and Management 2006;230:1–22.

[8] Begic F, Afgan NH. Sustainability assessment tool for the decision making in selection of energy system-Bosnian case. Energy 2007;32:1979–85.

[9] Burton J, Hubacek K. Is small beautiful? A multicriteria assessment of small-scale energy technology applications in local governments Energy Policy 2007;35:6402–12.

[10] Korhonen P, Moskowitz H, Wallenius J. Multiple criteria decision support – a review. European Journal of Operational Research 1992;63:361–75.

[11] Hayashi K. Multicriteria analysis for agricultural resource management: a critical survey and future perspectives. European Journal of Operational Research 2000;122:486–500.

[12] Løken E, Botterud A, Holen AT. Use of the equivalent attribute technique in multi-criteria planning of local energy systems. European Journal of Operational Research 2009;197:1075–83.

[13] Huang IB, Keisler J, Linkov I. Multi-criteria decision analysis in environmental sciences: ten years of applications and trends. Science of the Total Environment 2011;409:3578–94.

[14] Wang J, Jing Y, Zhang C, Zhao J. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews 2009;13:2263–78.

[15] Guitouni A, Martel J. Tentative guidelines to help choosing an appropriate MCDA method. European Journal of Operational Research 1998;109:501–21.

[16] Özcan T, Çelebi N, Esnaf Ş. Comparative analysis of multi-criteria decision making methodologies and implementation of a warehouse location selection problem. Expert Systems With Applications 2011;38:9773–9.

[17] Chatzimouratidis AI, Pilavachi PA. Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process. Energy Policy 2008;36:1074–89.

[18] Pilavachi PA, Roumpeas CP, Minett S, Afgan NH. Multi-criteria evaluation for CHP system options. Energy Conversion and Management 2006;47:3519–29.

[19] Chatzimouratidis AI, Pilavachi PA. Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process. Energy Policy 2009;37:778–87.

[20] Elghali L, Clift R, Sinclair P, Panoutsou C, Bauen A. Developing a sustainability framework for the assessment of bioenergy systems. Energy Policy 2007;35:6075–83.

[21] Madlener R, Kowalski K, Stagl S. New ways for the integrated appraisal of national energy scenarios: the case of renewable energy use in Austria. Energy Policy 2007;35:6060–74.

[22] Jovanović M, Afgan N, Radovanović P, Stevanović V. Sustainable development of the Belgrade energy system. Energy 2009;34:532–9.

[23] Diakoulaki D, Karangelis F. Multi-criteria decision analysis and cost-benefit analysis of alternative scenarios for the power generation sector in Greece. Renewable and Sustainable Energy Reviews 2007;11:716–27.

[24] Papadopoulos A, Karagiannidis A. Application of the multi-criteria analysis method Electre III for the optimisation of decentralised energy systems. Omega-International Journal of Management Science 2008;36:766–76.
[25] Doukas HC, Andreas BM, Psarras JE. Multi-criteria decision aid for the formulation of sustainable technological energy priorities using linguistic variables. European Journal of Operational Research 2007;182:844–55.
[26] Upham P, Shackley S, Waterman H. Public and stakeholder perceptions of 2030 bioenergy scenarios for the Yorkshire and Humber region. Energy Policy 2007;35:4403–12.
[27] Kaya T, Kahraman C. Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: the case of Istanbul. Energy 2010;35:2517–27.
[28] Ma J, Scott NR, DeGloria SD, Lembo AJ. Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. Biomass and Bioenergy 2005;28:591–600.
[29] Köne AÇ, Büke T. An Analytical Network Process (ANP) evaluation of alternative fuels for electricity generation in Turkey. Energy Policy 2007;35: 5220–8.
[30] Sheppard SRJ, Meitner M. Using multi-criteria analysis and visualisation for sustainable forest management planning with stakeholder groups. Forest Ecology and Management 2005;207:171–87.
[31] Baker D, Bridges D, Hunter R, Johnson G, Krupa J, Murphy J, et al. Guidebook to decision-making methods. USA: Department of Energy; 2002.
[32] Gamboa G, Munda G. The problem of windfarm location: a social multi-criteria evaluation framework. Energy Policy 2007;35:1564–83.
[33] Shih H, Shyur H, Lee ES. An extension of TOPSIS for group decision making. Mathematical and Computer Modelling 2007;45:801–13.
[34] Saaty TL. The analytic hierarchy process. New York: McGraw-Hill; 1980.
[35] Danielson M., Ekenberg L., Johansson J., Larsson A. The DecideIT decision tool. In: Proceedings of the third international symposium on imprecise probabilities and their applications. Lugano: Carleton Scientific; 2003.
[36] Brans JP, Mareschal B, Vincke P. PROMETHEE: a new family of outranking methods in multicriteria analysis. In: Brans JP, editor. Operational Research, IFORS, 84; 1984. p. 477–90.
[37] Sutter C. Sustainability check up for CDM projects.How to assess the sustainability of international projects under the Kyoto Protocol Christoph Sutter. Berlin: Wissenschaftlicher Verlag; 2003.
[38] Seyhan S, Mehpare T. The analytic hierarchy process and analytic network process: an overview of applications. Management Decision 2010;48: 775–808.
[39] Goumas M, Lygerou V. An extension of the PROMETHEE method for decision making in fuzzy environment: ranking of alternative energy exploitation projects. European Journal of Operational Research 2000;123:606–13.
[40] Cavallaro F, Ciraolo L. A multicriteria approach to evaluate wind energy plants on an Italian island. Energy Policy 2005;33:235–44.
[41] Saaty TL. There is no mathematical validity for using fuzzy number crunching in the analytic hierarchy process. Journal of Systems Science and Systems Engineering 2006;15:457–64.
[42] Belton V, Gear T. On a short-coming of Saaty's method of analytic hierarchies. Omega 1983;11:228–30.
[43] Triantaphyllou E. Multi-criteria decision making methods: a comparative study. Berlin: Springer; 2010.
[44] Keisler JM. The value of assessing weights in multi-criteria portfolio decision analysis. Journal of Multi-Criteria Decision Analysis 2008;15:111–23.